HIGH-POWER RADIO FREQUENCY/MICROWAVE (HPM) DIRECTED-ENERGY WEAPONS (DEWs) AND THEIR EFFECTS

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Outline

1. What Are HPM DEWs?
2. What Can HPM DEWs do for the Warfighter?
3. How Are HPM Weapons Different Than High-Energy Lasers?
4. How Are HPM DEWs Different From Traditional Electronic Warfare (EW) Jammers?
5. How Are HPM DEWs Similar to, but Different From Nuclear-Generated Electromagnetic Pulse (NEMP)?
6. How Does HPM Couple Into a Target?
7. What Types of Effects Does It Cause?
8. How Do We Protect Our Systems Against HPM Pulses?
9. Summary
10. Questions?
High Power Radio Frequency/Microwave (HPM) Directed-Energy Weapons (DEWs)

Also Known as Electromagnetic (EM) Weapons, Radio Frequency (RF) Weapons, Non-Nuclear EM Pulse, Electronic–Bombs (E-Bombs), Etc.

HPM DEWs Are EM Sources That:

- Generate and Direct Intense RF/Microwave Energy at an Electronic Target
  - Have Peak Effective Radiated Power of >100 MW or Radiated Energy >1 J per Pulse
  - Range in Frequencies From HF/VHF/UHF to Millimeter Wave

- Attack Targets With and/or Without Intentional RF Antennas/Receiver

- Produce Persistent Effects That Last Longer Than the Beam Is on Target (i.e., Temporary Electronic Upset and/or Damage)
  - “Unconventional Electronic Attack (UEA)”

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![Electromagnetic Spectrum Diagram](image_url)

- **f**: Frequency in Hz
- **λ**: Wavelength in meters

**VLF**: Very Low Frequency, **LF**: Low Frequency, **MF**: Medium Frequency, **HF**: High Frequency, **VHF**: Very High Frequency, **UHF**: Ultra High Frequency, **SHF**: Super High Frequency, **EHF**: Extremely High Frequency

**Radar Bands**: VLF, LF, MF, HF, VHF, UHF, SHF, EHF

**Visible Light**: 380–700 nm

**Infrared**: 0.76–8.0 μm

**Ultra Violet**: >8.0 μm
## Major Components of an HPM DEW

<table>
<thead>
<tr>
<th>HPM DEW</th>
<th>RF PROPAGATION</th>
<th>TARGET SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Prime Power</strong>&lt;br&gt;- Electrical Generator&lt;br&gt;- Explosives</td>
<td></td>
<td></td>
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<tr>
<td><strong>Pulse Power</strong>&lt;br&gt;- Capacitive&lt;br&gt;- Inductive (Pulse-Forming Network)&lt;br&gt;- High-Power Switches&lt;br&gt;  o  Tubes&lt;br&gt;  o  Solid State</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RF Source</strong>&lt;br&gt;<strong>Pulsed Continuous Wave (Narrow Band [NB] &lt;10% Center Frequency)</strong>&lt;br&gt;  - Magnetron Tube&lt;br&gt;  - Traveling Wave Tube (TWT) Amp&lt;br&gt;  - Klystron Amp&lt;br&gt;  - Gyrotron et al.&lt;br&gt;<strong>Transient Pulse (Wide Band [WB] &gt;25%f)</strong>&lt;br&gt;  - Spark Gap&lt;br&gt;  - Electronic Switches&lt;br&gt;  - Ferrite Lines</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Antenna</strong>&lt;br&gt;<strong>NB</strong>&lt;br&gt;  - High-Power Apertures&lt;br&gt;  - Higher Frequency&lt;br&gt;  - High Gain/Directivity&lt;br&gt;  - Well-Defined Pattern&lt;br&gt;<strong>Off-bore Site</strong>&lt;br&gt;  - Dipole/Transverse EM Horn&lt;br&gt;  - Lower Frequency&lt;br&gt;  - Less Gain&lt;br&gt;  - Less-Defined Pattern</td>
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<thead>
<tr>
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<th>What Can HPM DEWs Do for the Warfighter?</th>
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<tbody>
<tr>
<td>1</td>
<td><strong>Ability to ENGAGE MULTIPLE TARGETS</strong> at the “Speed of Light” (Instantaneous Fly-out, No Lead Angle). However, Effect May Not Be Instantaneous. Dwell Time Is Important.**</td>
</tr>
<tr>
<td>2</td>
<td><strong>PRODUCE “SCALABLE EFFECTS”</strong> From Temporary to Permanent Based on Target and RF Directed-Energy (DE) Range.</td>
</tr>
<tr>
<td>3</td>
<td><strong>HAVE “VERY DEEP MAGAZINES”</strong> — With Relatively Unlimited Number of “Low-Cost Ammo (DE Pulses).” Reduces Logistics and Associated Cost.</td>
</tr>
<tr>
<td>4</td>
<td>Provides <strong>HIGH PROBABILITY OF HIT</strong> Compared to Kinetic Energy Weapons and Lasers</td>
</tr>
<tr>
<td>5</td>
<td>Provides <strong>PLAUSIBLE DENIABILITY</strong>.</td>
</tr>
<tr>
<td>7</td>
<td>Operation and Maintenance <strong>SIMILAR TO RADAR</strong> Systems.</td>
</tr>
<tr>
<td>8</td>
<td>Typically <strong>NON-LETHAL TO HUMANS</strong>. Millimeter Waves Can Produce Temporary Pain, Crowd Control.</td>
</tr>
<tr>
<td>9</td>
<td>RF Protection Is Easy Theoretically, but <strong>MAY BE VERY DIFFICULT IN PRACTICE</strong>.</td>
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</tbody>
</table>
What Are Some Applications for Directed Energy Weapons?

**Airborne**
- Precision engagements
- Enables extended engagements
- Precision SEAD
- Offensive proactive fire support

**Land Based**
- Counter Air
- Vehicle Protection
- Counter Sensor/C4I
- Mine Clearing
- Precision Proactive Fire Support

**Future Combat System DEW**
- Indirect Fire w/ Directed Energy Munitions
- Enemy Sensor or C2
- UAV C2 Node
- MANPADS DEW
- LCR / MRL
- SAM
- TEL
- ABL
- DE Munitions
- HPM
- Enemy Sensor or C2

**Space Operations Area**

**Tactical Operations Area**
Power/Energy Technology Has Been an Enabler for DEWs?

**PHASE I – 2008**

- Mission times extended up to 6X
- Rechargeable batteries charged 2 – 3X faster
- Logistic fuels power the soldier
- 10X increase in power for non-propulsion uses
- Aircraft, 500 kW
- Enables dynamic armor

**PHASE II – 2015**

- Armor weight reduced up to 75%
- Ammunition weight reduced by 50%, volume by 67%
- Space payloads increased by 15%
- Fuel savings of 50% per ship
- Crew sizes reduced
- Reduced aircraft acquisition and maintenance costs
- Sorties per aircraft wing increased by 15%
- Aircraft, multi-megawatt
Types of HPM Sources

NB delivers burnout punch, while WB/ultra-wide band (UWB) can be repetitively pulsed at high rates for upset since its pulses contain little energy.

<table>
<thead>
<tr>
<th>Time Domain</th>
<th>Frequency Domain</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow Band</td>
<td></td>
<td>Best for Maximizing Energy per Pulse</td>
</tr>
<tr>
<td><img src="image" alt="Narrow Band" /></td>
<td><img src="image" alt="Frequency Domain" /></td>
<td></td>
</tr>
<tr>
<td>Wide Band</td>
<td></td>
<td>Best for Maximizing Peak Power</td>
</tr>
<tr>
<td><img src="image" alt="Wide Band" /></td>
<td><img src="image" alt="Frequency Domain" /></td>
<td>Minimizes Intel Requirements Since Matching Source and System $f_0$ Are Not Required</td>
</tr>
</tbody>
</table>

$E(t)$ represents the electric field over time, where $f_0 = 1/Dt$ represents the frequency at which the pulse occurs.
Examples of HPM DEW Systems

- **POWER SUPPLY**: U.S. Air Force (AF) Tactical High-Power Microwave Operational Responder (THOR)
- **HPM SOURCE/TRANSMITTER**: Small-Truck-Mounted NB HPM Source
- **ANTENNA/RADIATOR**: UWB Source With Impulse Radiating Antenna
HPM DEWs Provide Unconventional Electronic Attack (UEA)

TARGET EFFECTS
- Electronic Interference
- Electronic Damage/Defeat
- Structure/Physical

Electronic Warfare (EW)
- Electronic Protect
- Electronic Attack (EA)
- Electronic Support

Persistent Effects on ALL Electronics

- UEA
- DEWs

- Neutral/Charged Particle Beams
- High-Energy Lasers
- HPM

Temporary Effects on Sensors/Receivers Only
- Traditional EA
  - Jammers
EA Traditional Jamming and HPM DEW

**TARGET EFFECTS**
- Green: Temporary Interference
- Yellow: Longer-Term Upset
- Red: Permanent Damage

Jamming Generally Requires Less Power but Is Limited to Targets With RF Receivers and Produces Temporary Effects.

HPM May Require Greater Power, but Can Attack Targets Without Receivers and Produce Long-Term Effects ("Persistent Effects").

**TARGET KNOWLEDGE**
- Out-of-Band (Pulse Modulation)
- Deception Jamming (In-Band – Know Frequency)
- Denial/Noise Jamming (In-Band – Know Frequency)

**RF POWER DENSITY ON TARGET**
- uW/cm²
- mW/cm²
- W/cm²
- KW/cm²
**Technology**

- **Solid-State RF Amplifiers**
- **Digital RF Memory**
- **High-Power RF Tubes** (Magnetron, TWTs)

**RF Power Density on Target**

- **kW/cm²**
- **W/cm²**
- **mW/cm²**
- **μW/cm²**

**Target Response**

- **Interference**
  - In-Band Modulation: WB, Spread Spectrum
  - Out-of-Band Modulation: WB Noise
  - Out-of-Band Modulation: Repetitive Pulses/Freq Hop

- **Upset**
  - Out-of-Band Modulation: Repetitive Pulses

- **Damage**
  - Out-of-Band Modulation: Impulse
How Does HPM Differ From NEMP?

1. NEMP Is Single Shot, While HPM May Be Repetitively Pulsed.

2. Frequency Regimes Differ So That Resonant Coupling of Energy Into a Target Occurs at Different Characteristic Lengths.

<table>
<thead>
<tr>
<th></th>
<th>TYPICAL FREQUENCIES</th>
<th>CHARACTERISTIC LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEMP</td>
<td>DC to 100 MHz</td>
<td>3 m or more</td>
</tr>
<tr>
<td>WB RF</td>
<td>~30 MHz to ~3 GHz</td>
<td>~10 cm to ~10 m</td>
</tr>
<tr>
<td>NB HPM</td>
<td>~1 GHz and up</td>
<td>Up to 30 cm</td>
</tr>
</tbody>
</table>
How Does HPM Differ From NEMP?

3 ASSESSMENT SIMILARITIES:

• Both Address Complex RF Coupling Into Targets and Require Numerous Variables to Describe Effect Levels.

• Limited Facilities and Test Objects Sometimes Force Reliance on Low-Power Tests and Analysis.

4 ASSESSMENT DIFFERENCES:

• The NEMP Threat Is Usually an "Official Threat" So That Some Variables Are Constrained. There Is No Well-Defined HPM Threat; Numerous Parametric Excursions Are Required.

• Systems Within a Given Class Are More Similar on NEMP Length Scales.

• Computer Models of Complex Systems Must Include More Detail for NB HPM.
NEMP vs. HPRF/M

How Does HPM Couple Into Targets?

Intentional Antennas/ Receivers (Front Doors)
- In-Band RF
- Out-of-Band RF

Unintentional Antennas/ Receivers (Back Doors)

Antenna
(Gain/Effective Area)

Signal Path
(Path Loss)

Sensitive Electronics
(Component Effect Level)

Apertures, Seams, Etc.
(Unintentional Antenna)

Coupling

RF Energy Can Enter Target via Intentional Antennas [i.e., “Front Doors”] or via Unintentional Antennas (i.e., Apertures, Cables, etc.) [i.e., “Back Doors”].
HPM DEW Effects on Electronics

Effects Depends on HPM Source Power and Range

TEMPORARY INTERFERENCE
System Recovers When Beam Is Removed (i.e., Jamming).

LONGER-TERM UPSET
System Recovers After Reset.

PERMANENT DAMAGE
System Recovers ONLY After Repair/Replacement.

Effects Are Statistical Quantities Expressed in Terms of Probability of Effect (i.e., Upset/Damage).
Types of HPM Effects Experiments

**DIRECT-INJECTION EXPERIMENTS**
- Directly Couple Selected HPM Waveform Into Target
- Establish Upset and Damage Thresholds
- Evaluate Pulse Width and Pulse Rep Frequency (PRF) Effectiveness
- Determine Optimum Frequency and Bandwidth for Selected Asset

**FREE-FIELD/CHAMBER EXPERIMENTS**
- Radiate Target in RF Chamber or Outdoors
- Use HPM Source With Specified Parameters and Diagnostics
- Observe/Measure Target Responses vs. Incident Energy
Electronic Attack Scenario and Key Parameters

Electronic Attack Source
- Transmitter Power (P)
- Frequency/Wave Length (f) / (λ)
- Antenna Gain (G)
- Pulse Duration/Width (τ)
- PRF (F)
- Angle (θ, φ)
- Wave Polarization, p

Propagation
- Range (Space Loss) (R)
- Atmospheric Losses (La)
  - Losses Low for Lower Frequencies

Target Effects
- EA Power Received
- Electronic Effect Level (C)

\[ S_{EA} = \text{Power Density on Target} = \frac{(P)G}{4\pi R^2} \]

\[ \text{EA Power at Electronics} = P_{EA} = (S_{EA} A_e) L \]

\[ \text{Desired Signal} = (P_{\text{Normal}}) A_e L \]

Difference Between Jamming and Persistent Effects Is:
- Probability of Jamming: Probability \{P_{EA} > \text{Desired Signal}\}
- Probability of RF DE Damage: Probability \{P_{EA} > C\} = Probability of \{(S_{EA} A_e L) > C\}
# Target Effects and Downtime

RF DE Can Produce Effects That Range From Interference to Temporary Disruption to Damage of Target Electronics.

<table>
<thead>
<tr>
<th>FAILURE MODE</th>
<th>POWER NEEDED</th>
<th>WAVE SHAPE NEEDED</th>
<th>RECOVERY PROCESS</th>
<th>DOWNTIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference or Analog Upset</td>
<td>Low</td>
<td>Repetitive Pulse or Continuous</td>
<td>Self-Recovery After Exposure Stops</td>
<td>Seconds</td>
</tr>
<tr>
<td>Digital Upset</td>
<td>Medium</td>
<td>Short Pulse Single or Repetitive</td>
<td>Operator Intervention</td>
<td>Minutes</td>
</tr>
<tr>
<td>Memory Corruption</td>
<td>Medium</td>
<td>Short Pulse Repetitive</td>
<td>Maintenance Intervention</td>
<td>Hours</td>
</tr>
<tr>
<td>Damage</td>
<td>High</td>
<td>Short Pulse (UWB) Longer Pulse (Narrow)</td>
<td>Maintenance Intervention</td>
<td>Days</td>
</tr>
</tbody>
</table>

## General Observations

- Mission Impact of Failure Depends on When Exposure Occurs.
- Damage Mode Is Most Lethal but Hardest to Implement.
- Digital Upset or Memory Corruption Can Be Lethal and Is Easier to Implement.
High Power Radio Frequency/ Microwave Protection Guides

HPRF/M Hardening Design Guide for Systems
• HDL-CR-92-709-5, U.S. Army Research Laboratory (ARL), April 1992

• Estimates Voltage Induced vs. Component Strength

Military Systems:
• Army Hardening Demonstration on IFF (ARL)
• AF Hardening Demonstration F-16 and LANTIRN (AFRL/DE)

Commercial Systems
• Aircraft (e.g., Cooperative Research and Development Agreement with Boeing for Test Chamber)
• Computers
Summary

HPM DEW Provides Warfighters With:
- High Probability of Hit
- “Speed of Light” Engagements for Multiple Targets in Near-All-Weather Conditions
- Scalable Target Effects (Temporary to Permanent – Non-Lethal to Lethal)
- Relatively Low Cost Per Shot

HPM Provides Additional Electronic Attack/Warfare Capability
- Out-of-Band Attack on Targets With and Without Receivers
- Possibility to Attack Target Classes - Requires Little-to-No Target Information
- Long-Term to Permanent Effects (Damage)

Effects Levels Depend Upon HPM DE Source/Target Parameters
- Effect Levels Typically Measured Over Limited Parameter Space Due to Source Availability

Impact of Effects on Mission May Be Difficult to Determine

Protection/Countermeasures Technically Possible – May NOT be Easy
- RF Protection Designed-In – 1% to 15% Total System Cost
- Retro-Fit Hardening – 20% to 90% of Total System Cost
  - “Pay Now or Pay Later”